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Lifetime Measurements in ^{162}Dy

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Abstract

Background: The nature of oscillations or excitations around the equilibrium deformed nuclear shape remains an open question in nuclear structure. The ^{162}Dy nucleus is one of the most extensively studied nuclei with the (n, γ), (n, e^-), (α,2n) reactions and most recently the (p, t) pickup reaction adding eleven 0^+ states up to an excitation energy of 2.8 MeV to an already well developed level scheme. However, a major shortfall for a better understanding of the nature of the plethora of bands and levels in this nucleus has been the lack of lifetime measurements. **Purpose:** To determine the character of the low-lying excited bands in this ^{162}Dy nucleus, we set out to measure the level lifetimes. **Method:** Lifetimes were measured in the ^{162}Dy nucleus following neutron capture using the GRID (Gamma Ray Induced Doppler broadening) technique at the Institut Laue-Langevin (ILL) in Grenoble, France. **Results:** In total, we have measured the lifetimes of twelve levels belonging to a number of excited positive and negative parity bands in the low-lying spectrum of the ^{162}Dy nucleus . The lifetime of the $\mathrm{K}^\pi = 2^+$ bandhead at 888.16 keV was previously measured. We confirm this value and measure lifetimes of the 3^+ and 4^+ members of this band yielding B($E2$) values that are consistent with a single γ-vibrational phonon of several Weisskopf units (W.u.). The first excited $\mathrm{K}^\pi = 4^+$ band, with a band head at 1535.66 keV, is strongly connected to the $\mathrm{K}^\pi = 2^+$ band with enhanced collective B($E2$) values and it is consistent with a double phonon vibrational ($\gamma\gamma$) excitation. Lifetime of $\mathrm{K}^\pi = 0^+$ band members have also been measured including the $4^+_{K^\pi=0^+_2}$ state at 1574.29 keV and the $2^+_{K^\pi=0^+_3}$ state at 1728.31 keV. This latter state also displays the characteristics of a double phonon excitation built on the $K^\pi = 2^+$ band. **Conclusions:** We discuss our findings in terms of the presence or absence of collective quadrupole and octupole vibrational excitations. We find two positive parity excited bands at 1535.66 keV ($\mathrm{K}^\pi = 4^+$) and the 1728.312 keV 2^+ state of a $\mathrm{K}^\pi = 0^+$ band at 1666 keV connected with sizably collective B(E2) values to the ($\mathrm{K}^\pi = 2^+$) γ band at 888 keV.

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I. INTRODUCTION

The existence and characterization of multi-phonon vibrational modes in deformed nuclei remains an open question in nuclear structure. The question revolves around the possible degrees of freedom in deformed nuclei [1–4]. Rotational motion is an expected feature of deformed nuclei, the open challenge is whether the "granularity" of nuclei [1] allows single or multiple quanta of vibrational oscillations or excitations superimposed on the equilibrium deformed shape of the nucleus.

The lowest lying such shape effecting oscillations or vibrations would be quadrupole ($\lambda = 2$) in nature, resulting in two types of vibrations: β with no projection on the symmetry axis and γ with a projection of $\mathrm{K}^\pi = 2^+$. Vibrational spectra can, in principle, be constructed from one or more quanta of these states resulting in two-phonon $\beta\beta$ ($\mathrm{K}^\pi = 0^+$), $\beta\gamma$ ($\mathrm{K}^\pi = 2^+$), and $\gamma\gamma$ ($\mathrm{K}^\pi = 0^+$ and 4^+) types of vibrational excitations. Single phonon γ vibrational bands and low-lying $\mathrm{K}^\pi = 0^+$ bands have been known for some time and they are abundant in various regions of deformation, including the rare-earth region of nuclei, albeit without systematic knowledge of level lifetimes. The γ vibration seems to be well characterized as the first $\mathrm{K}^\pi = 2^+$ (2^+_γ) band and exhibits a systematic behavior across the region of deformed nuclei with typical $B(E2; 2^+_\gamma \to 0^+_{g.s.})$ values of a few Weisskopf units (W.u.). Figure 1 shows the energies of the first excited $\mathrm{K}^\pi = 2^+$ and the first excited $\mathrm{K}^\pi = 0^+$ (0^+_2) bands in several isotopes of Sm, Gd, Dy, Er, Yb, and Hf as a function of neutron number "N" along with the observed $B(E2; 2^+_\gamma \to 0^+)$ values for the γ bands and the $B(E2; 0^+_2 \to 2^+_{g.s.})$ values. The top part of this figure shows the energies of the γ and 0^+_2 bands with very different behavior. The γ band energies are roughly flat beyond $N = 90$ to approximately $N = 102$ and the corresponding B($E2$) values are similarly flat in the same region showing B($E2$) transitions that are several Weisskopf units (W.u.) in strength. The energies of 0^+_2 bands and the $B(E2; 0^+_2 \to 2^+_{g.s.})$ values show a different picture. The energies of the band heads of 0^+_2 bands seem to display a parabolic shape, increasing from $N = 90$ to 96 and then decreasing. The B($E2$) values are sparse in the region and, where available, do not exhibit a consistent behavior. The question regarding the viability of the $\mathrm{K}^\pi = 0^+$ excitations as the "β-vibration" in deformed nuclei remains open to discussion and debate [1, 5–10].

There are however several examples of two-phonon quadrupole vibrational excitations in a number of nuclei exhibiting various degrees of the full collective transition strength with

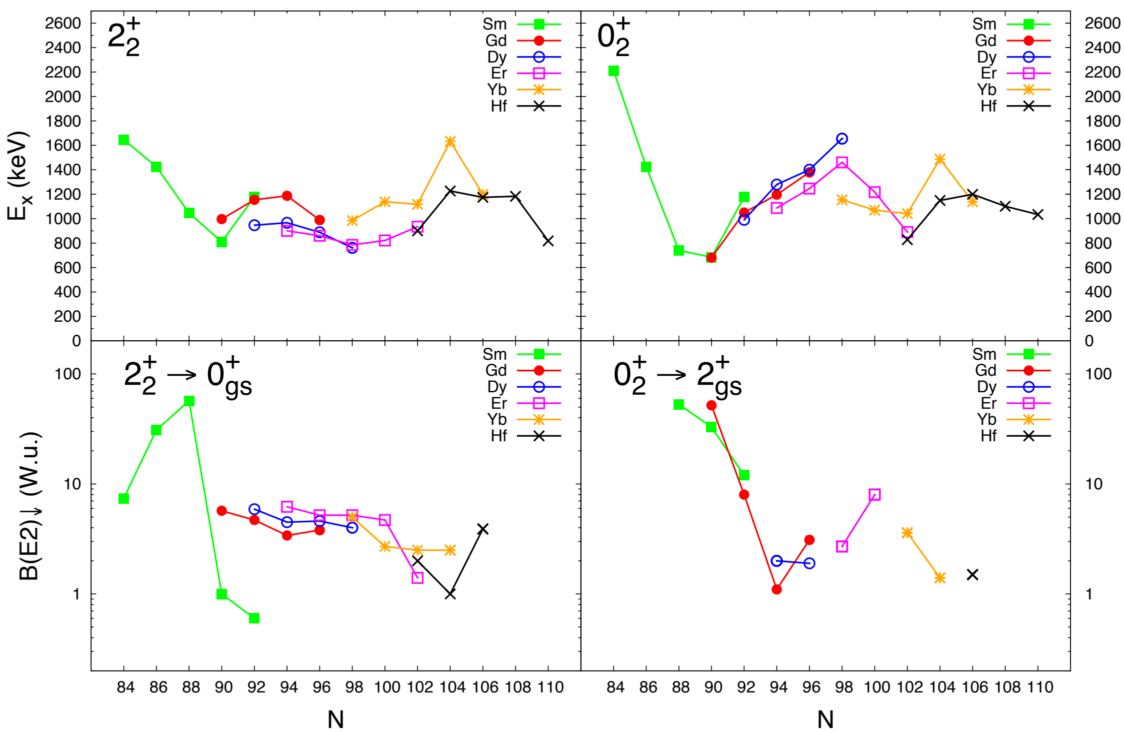

FIG. 1: (color online) Systematics of the first excited $K^\pi = 2^+$ "γ" and $K^\pi = 0^+$ bands in several isotopes of Sm, Gd, Dy, Er, Yb, and Hf as a function of neutron number "N" along with the observed $B(E2; 2^+_{K=2^+} \rightarrow 0^+)$ values for the γ bands and the $B(E2; 0^+_2 \rightarrow 2^+_{g.s.})$ values for the first excited $K^\pi = 0^+$ bands.

wide ranges in energy anharmonicities [11–24].

Octupole vibrational quanta with $\lambda = 3$ are expected to be split into $K^\pi = 0^-$, 1^-, 2^- and 3^- bands in the field of a deformed nucleus. In fact, there were nine negative parity bands identified in ^{162}Dy. The goal in this work is to contribute to the discussion on the viability of single and double phonon quanta of vibrational excitations by the measurement of lifetimes in ^{162}Dy.

The ^{162}Dy nucleus has been studied extensively in the past by a variety of reactions and methods. It was studied via β-decay of ^{162}Tb [25], by electron capture decay of ^{162}Ho [26, 27], by (n, γ) of ^{161}Dy and $(n, n'\gamma)$ of ^{162}Dy [28–32], by (α,2n) [33], by a number of transfer reactions including (d, p) [28, 34], (d, t) [28], (p, t) [35, 36], (t, p) [37], (d, d') [38], (α,^{3}He) [39], (^{3}He,α) [39], by quasielastic heavy-ion transfer near barrier energies $(^{61}Ni,^{60}Ni)$ on ^{161}Dy [40] and by coulomb excitation [41]. Ref. [29] used the technique of average resonance neutron capture with neutron beams of a mean energy of 2 and 24 keV. The averaging process guarantees the observation of a complete set of states of $J^\pi = 1^\pm, 2^\pm, 3^\pm, 4^\pm$ up to an excitation energy of 2 MeV.

A relatively recent study [42] also reported on measurements by (n, γ), (n, e^-), and $(\alpha, 2n)$ reactions in order to provide a complete set of energy levels and depopulating transitions. The $(n, \gamma)$and (n, e^-) measurements were carried out at the Institute Laue-Langevin (ILL) exploiting the exceptional precision of the GAMS 2/3 and BILL spectrometers. The $(\alpha, 2n)$ reaction was carried out at the Lawrence Berkeley National Laboratory (LBL) 88" cyclotron using the HERA array of 21 Compton-suppressed Ge detectors. The result was an extensive level scheme up to 4 MeV with guarantees of completeness up to an excitation energy of 2 MeV for spins of $J^\pi = 1^\pm, 2^\pm, 3^\pm, 4^\pm$.

This current work reports on measurements of lifetimes in ^{162}Dy using the GRID (Gamma Ray Induced Doppler broadening) technique at the Institute Laue Langevin's ILL neutron flux reactor using the (n,γ) reaction to populate states in this nucleus. The following section presents the experimental details and results and the implications of the results are presented in the discussion.

II. EXPERIMENT

Lifetimes of the levels in ^{162}Dy were measured using the neutron high flux reactor at the Institute Laue-Langevin (ILL) in Grenoble, France in three dedicated runs. The 95% enriched Dy_2O_3 targets were between 900 and 100 mg and inserted into position 50 cm from the reactor core. The GRID technique [43] of lifetime measurements is based on measuring the broadening of decay gamma-ray lines using perfect crystals to measure the associated wavelength of a γ-ray. The broadening is due to the initial recoil velocity of the nucleus where the width of a given gamma-ray transition emitted in flight results from the competition between the slowing down process and the level lifetime. Knowing the slowing down process from simulations, we are able to extract the nuclear level lifetime. The recoil velocities are typically 10^{-4}c to 10^{-6}c, giving a broadening of only a few eV. The high precision comes from the energy resolution of the double-flat-crystal spectrometer GAMS4 [44–47]. The γ-ray wavelengths rely on crystal diffraction from nearly perfect flat crystals made of silicon or germanium. GAMS4 is a double-flat-crystal spectrometer with remarkable energy resolution. The broadened γ-ray peaks were fit using the code GRIDDLE [48]. The largest uncertainties in these measurements arise from the unknown feeding of the level of interest. Therefore, in cases where the feeding of a particular nuclear level is not completely understood, rather extreme assumptions have been made in order to extract conservative *upper* and *lower* limits. The upper limit of the extracted lifetime is determined assuming that the level is totally fed by cascades of γ-ray transitions from the compound capture state. The lower limit is extracted by assuming that the missing feeding comes from the unplaced low energy transitions that were measured in this nucleus. The more realistic scenario would probably lie somewhere in the middle of the lifetimes resulting from these intentionally extreme feeding assumptions. The measured lifetimes are listed in Table I. Included are four measured lifetimes for the states of interest. We have remeasured three of these and an additional 9 states for the first time. All levels are discussed in detail below.

III. RESULTS

The known levels of ^{162} Dy below an excitation energy of 2.0 MeV [42] are shown in Fig. 2. In total, 12 level lifetimes were measured in this work and are indicated in red. The

TABLE I: The GRID level lifetimes in ^{162}Dy measured in this work along with previously measured level lifetimes. The table shows the energies of the levels, their spin and parity assignments, the formerly known lifetimes with references, the GRID result, and in the last column, the lifetime $\tau = 0.6\tau_{max}$ used for discussion. The lifetimes extracted from the GRID measurements are correctly listed as a range of lifetimes as discussed in the experimental section that result from the extreme assumptions made for the missing feeding of a given level.

E_L (keV)	K,J^π	τ (ps)	τ_{GRID} (ps)	$\tau = 0.6\tau_{max}$ (ps)
888.158	2,2^+_γ	2.83 (11) [49]	1.07 – 4.67	2.8
962.936	2,3^+_γ	–	0.36 – 4.09	2.4
1060.986	2,4^+_γ	–	0.708 – 3.17	1.90
1148.226	2,2^-	300 (60) [51]	–	–
1275.767	0,1^-	0.029 (5) [52]	< 0.22	–
1357.923	0,3^-	–	< 0.21	–
1485.666	5,5^-	2780 (190) [53]	< 2.91	–
1518.420	0,5^-	–	< 0.19	–
1535.660	4,4^+	–	0.15 – 5.2	3.1
1574.288	0,4^+	–	1.08 – 3.1	1.9
1728.312	0,2^+	–	0.25 – 1.0	0.6
1862.672	4,4^-	–	1.58 – 2.86	1.7
1910.422	2,3^-	–	0.25 – 0.30	0.18

level at 888.16 keV has an inferred lifetime of $\tau = 2.83$ (11) ps from Coulomb excitation measurements [49]. The range of lifetimes extracted from GRID is 1.07 – 4.67 ps. This lifetime corresponds to 0.6 times the GRID upper limit which will be used for discussion. B($E2$) values that correspond to the upper and lower limits of the extracted lifetimes are also calculated. In the future when the remaining level feeding is determined, these lifetime ranges can be narrowed down significantly. In this paper, we use a factor of 0.6 following the approach introduced by H. G. Börner *et al.* [50] with the normalization to the one known level lifetime.

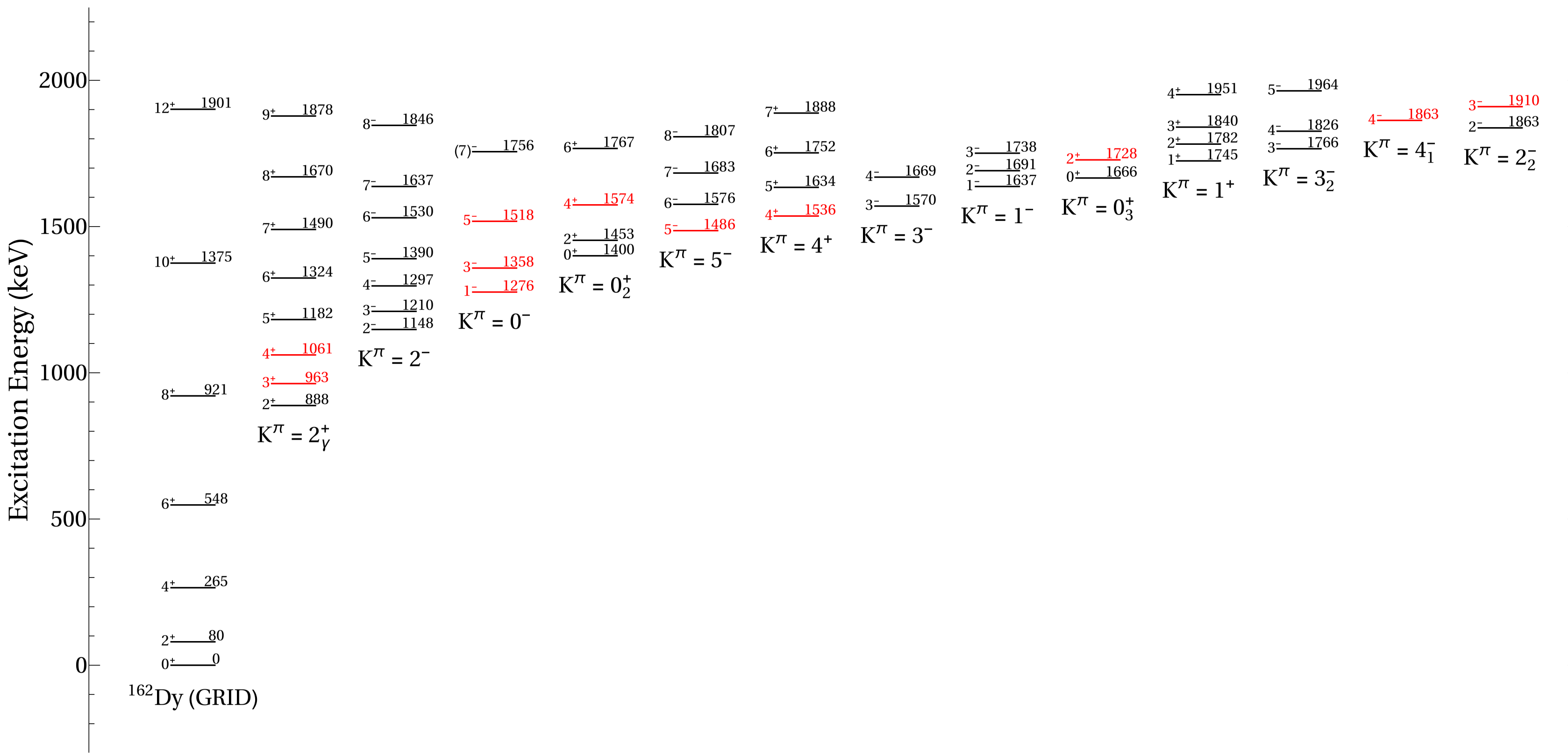

FIG. 2: All levels of interest in ^{162}Dy below 2 MeV. The twelve level lifetimes measured in this work are highlighted in red.

A. Positive Parity Levels

Seven levels from several positive parity bands have been measured and these include, three states within the $K^\pi = 2^+$ band at 888.16, 962.94, and 1060.99 keV, one state within the first excited $K^\pi = 0^+$ band at 1574.29 keV, one state within the $K^\pi = 4^+$ band at 1535.66 keV, and one state from the second excited $K^\pi = 0^+$ band at 1728.31 keV. Level lifetimes are given in Table I and Table II lists the extracted B($E2$) or B($E1$) values using known multi polarities of the depopulating transitions or in some cases the deduced multi polarities. The latter are presented in parenthesis in Table II. A more selected summary of the resulting B($E2$) values for the depopulations of the positive parity states are shown in Fig. 3.

1. $K^\pi = 2^+$ Band at 888.16 keV

This $K^\pi = 2^+$ band (2^+_γ) is known up to spin 9^+ [42]. The 2^+ band head at 888.16 keV has a known lifetime inferred from Coulomb excitation of 2.83 ± 0.11 ps [49]. Our measured value for the 2^+ within the restrictions discussed above is 1.07 – 4.67 ps. If we normalize the coulex value to our range of measured lifetimes, we get a multiplication factor of 0.6 of the upper limit. This is a reasonable factor since 60% of the feeding of this level is known and we have modeled the missing 40% of the feeding in the manner described above in the experiment section. We calculate B($E2$) values from the $2^+_\gamma \rightarrow 0^+_{g.s.}$: $2^+_\gamma \rightarrow 2^+_{g.s.}$: $2^+_\gamma \rightarrow 4^+_{g.s.}$ transitions as given in Table II of [4.7 : 8.0 : 0.6 W.u.] or [0.025 : 0.042 : 0.0031 e^2b^2]. The Alaga rules for these transitions are [1 : 1.4 : 0.08] in good agreement with the experimental values of [1 : 1.7 : 0.1]. If we apply the same factor of 0.6, a comparison can be made of the absolute B($E2$) values with the Alaga rules for the 3^+ and 4^+ states as well. The Alaga values for the $B(E2; 3^+_\gamma \rightarrow 2^+_{g.s.})$: $B(E2; 3^+_\gamma \rightarrow 4^+_{g.s.})$ are [1.0 : 0.4] in comparison to the experimental values of [1 : 0.6]. The Alaga rules for the $B(E2; 4^+_\gamma \rightarrow 2^+_{g.s.})$: $B(E2; 4^+_\gamma \rightarrow 4^+_{g.s.})$: $B(E2; 4^+_\gamma \rightarrow 6^+_{g.s.})$ transition rates are [1.0 : 2.9 : 0.26] in comparison with the experimental rates of [1.0 : 4.7 : 0.7]. Looking broadly to the collectivity ranges of the observed absolute B($E2$) transitions from this $K^\pi = 2^+$ band, they vary from a few to several Weisskopf units and are in the same range as those typically observed for γ vibrational excitations in deformed nuclei of the rare earth region as shown in Fig. 1.

2. $K^\pi = 0_2^+$ Band at 1400.26 keV

The K=0^+ assignment of this band at 1400.26 keV was originally made from the β decay of ^{162}Ho and confirmed by Ref. [26, 42]. In this experiment, we were only able to measure the lifetime of the 4^+ state of this band at 1574.29 keV with a number of transitions depopulating to the K$^\pi$ = 2^+ band and the K$^\pi$ = $0^+_{g.s.}$ band. The Alaga ratio for the $B(E2; 4^+_{K^\pi=0^+} \rightarrow 4^+_{g.s.})$: $B(E2; 4^+_{K^\pi=0^+} \rightarrow 6^+_{g.s.})$ is [1.0 : 1.75] while the experimental ratio is [1.0 : 0.4]. The other transitions from this level connect to the $2^+, 3^+, 4^+$ and 5^+ states of the K$^\pi$ = 2^+ gamma band.

The Alaga rules for the ratios of B($E2$) values are $B(E2; 4^+_{K^\pi=0^+_2} \rightarrow 2^+_\gamma)$: B(E2;$4^+_{K^\pi=0^+_2} \rightarrow 3^+_\gamma$): B(E2;$4^+_{K^\pi=0^+_2} \rightarrow 4^+_\gamma$):B(E2;$4^+_{K^\pi=0^+_2} \rightarrow 5^+_\gamma$) are [1 : 14 : 44 : 49] in comparison to experiment values of [1.0 : 0.7 : 7.6 : 13]. Table II lists the absolute B($E2$) values as well as the Alaga rules. The ranges of B($E2$) values for transitions depopulating this level range from 0 to several W.u. making it impossible for us to make a definitive conclusion about the nature of this K$^\pi$ = 0^+ band.

3. $K^\pi = 4^+$ Band at 1535.66 keV

This band is known up to J$^\pi$ = 11^+ as populated in an $(\alpha, 2n)$ reaction [42]. In this (n, γ) measurement, a 0.15 to 5.1 ps range of lifetimes was measured for this 4^+ band head state. Using the 0.6 factor discussed previously, τ = 3.1 ps is used. The one transition from this level depopulating to the $4^+_{g.s.}$ is orders of magnitude weaker than the transitions populating the 2^+, 3^+, 4^+, and 5^+ members of the K$^\pi$ = 2^+ γ band. All indications are that this level is an excitation built on top of the K$^\pi$ = 2^+ "γ" band.

4. $K^\pi = 0^+$ Band at 1666.27 keV

The level at 1666.27 keV has a spin and parity of 0^+ and it was confirmed in the recent (p, t) measurement [36]. In this work, we report on the lifetime of the 2^+ state at 1728 keV . The Alaga rules support the placement of these two levels into a K$^\pi$ = 0^+ band.

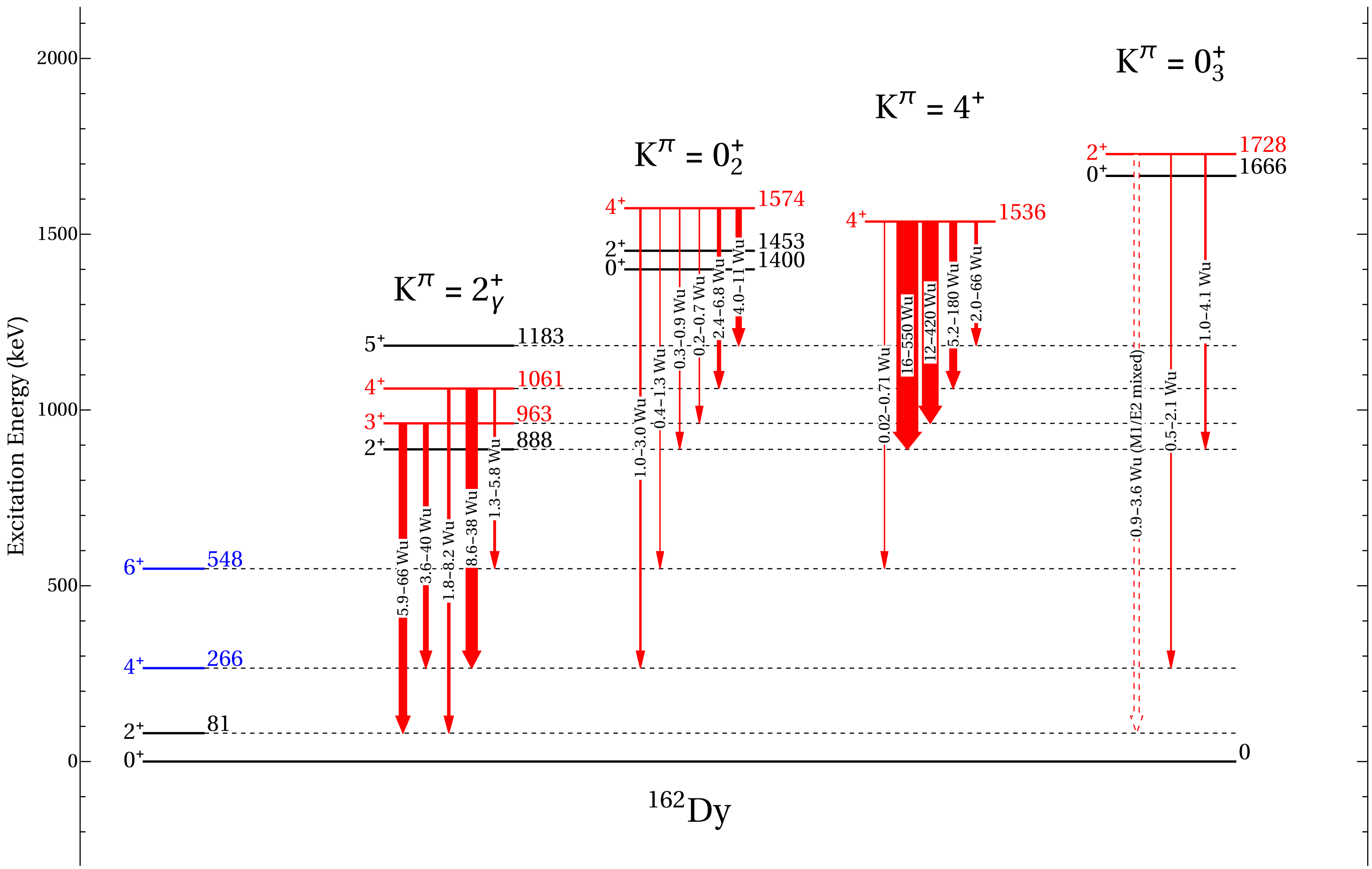

FIG. 3: Partial decay scheme for the positive parity K$^{\pi}$ levels in ^{162}Dy.

The 1647.617 keV transition was reported as M1 in the earlier comprehensive study of this nucleus[42]. In more recent work with a measurement of angular distributions, this transition multipolarity has been determined to be E2/M1 [58]. The transition is listed as E2/M1 in Table II and both B(M1) and B(E2) values are calculated. The Alaga rules for a $K^\pi = 0^+$ to a $K^\pi = 0^+_{g.s.}$ set of $B(E2)$ values for the $B(E2; 2^+ \rightarrow 2^+_{g.s.}) : B(E2; 2^+ \rightarrow 4^+_{g.s.})$ is [1 : 1.8] in comparison with the experimental numbers of [1 : 2]. If we consider the 1728.31 keV state as being a band head or a $K^\pi = 2^+$ band, the Alaga rules would be [1 : 0.05] in disagreement with the experimental values. We can confirm that this is a 2^+ state of a $K^\pi = 0^+$ band.

B. Negative Parity Levels

Negative parity bands in deformed nuclei are thought to arise from a variety of methods; the fragmentation of octupole vibrational strength through coupling with quadrupole degrees of freedom, from stable octupole deformations, or quasi-particle excitations. In the actinide region of nuclei, octupole deformations are well known and observed as bands of parity doublets, while in the deformed rare-earth region, we can explore in detail the octupole degrees of freedom in the presence of stable quadrupole deformation. The octupole excitation in deformed nuclei is known to split into a set of vibrational bands of $K^\pi = 0^-$, 1^-, 2^-, and 3^- bands. In ^{162}Dy, there are a multitude of negative parity bands that have been observed including two $K^\pi = 2^-$ bands, a $K^\pi = 0^-$ band, a $K^\pi = 5^-$ band, two $K^\pi = 3^-$ bands, a $K{=}1^-$ band, and a $K^\pi = 4^-$ band. We have not succeeded in measuring lifetimes within the $K^\pi = 3^-$ or the $K{=}1^-$ bands in this work. We report a limit on the 5^- state at 1485.67 keV. The $K^\pi = 5^-$ band is likely a quasi-particle excitation and can provide guidance to the absolute strength of non-collective $B(E1)$ transitions in ^{162}Dy. $B(E1)$ values in the rare-earth region have been shown to exhibit hindrance factors of 10^3 to 10^9 with respect to single particle estimates [54, 55]. A hindrance factor is defined as the ratio of Weisskopf $B(E1)$ value divided by the measured $B(E1)$. Enhanced B(E1) values are recognized [55] as signatures of octupole vibrational degrees of freedom interacting with the quadrupole deformed ground state. There is also an enhancement of $B(E1)$s between states of the same K, and we see it here as well with $B(E1)$ values between $\Delta K = 0, 2$, and 4 states. We also report limits on the lifetimes of two states from the $K = 0^-$ band at starting at 1275.77

keV. We report the lifetime of the the 4^- state at 1862.67 keV and the 3^- state of the second excited $K = 2^-$ band starting at 1862.67 keV. Below we discuss the absolute B($E1$)s and B($E2$)s depopulating these negative parity bands in order of excitation energy of the level. Fig. 4 shows the ranges of absolute B($E1$) and B($E2$) transition probabilities for the negative parity levels whose lifetimes have been measured in this work.

1. $K^\pi = 2^-$ band at 1148.23 keV

The 2^- state at 1148.23 keV had a previously measured lifetime of 300±60 ps [51] and identified as the 2^- of the octupole vibration [56, 57], resulting in B($E1$) transitions of 0.028 e^2b and 0.017 e^2b to the 2^+ and 3^+ members of the $K^\pi = 2^+$ gamma band.

The ratio of B($E1$) values for the B($E1; 2^- \to 2^+_{K^\pi=2^+}$) : B($E1; 2^- \to 3^+_{K^\pi=2^+}$) is [1 : 0.6] consistent with the Alaga values for these two transitions of [1 : 0.50]. These B($E1$) values are highly enhanced compared to traditional $E1$ transitions in the rare earth region most likely due to ΔK=0.

2. $K^\pi = 0^-$ band at 1275.77 keV

Levels built on this $K^\pi = 0^-$ band [42] are known to 13^-. We were able to extract upper limits for the level lifetimes of the 3^- and the 5^- states in this band and therefore lower limits on the B($E1$) values for transitions depopulating these two levels. The 3^- state at 1357.92 keV depopulates to the 2^+ and 4^+ ground states. The ratio of B($E1; 3^-_{K^\pi=0^-} \to 2^+_{g.s.}$) : B($E1; 3^-_{K^\pi=0^-} \to 4^+_{g.s.}$) values from experiment is [0.9 : 1] in good agreement with the Alaga rules prediction of a ratio of [0.75 : 1]. Similarly, for the 5^- state of the same band at 1518 keV, the ratio of B($E1; 5^-_{K^\pi=0^-} \to 4^+_{g.s.}$): B($E1; 5^-_{K^\pi=0^-} \to 6^+_{g.s.}$) is [1.0 : 0.90] experimentally in comparison to the Alaga predicted ratio of [1 : 1.2] .

3. $K^\pi = 5^-$ band at 1485.67 keV

Levels built on this band [42] are also known to 13^- . This level had a previously measured lifetime of 2780 ± 190 ps from the decay of ^{162}Ho [53]. We extract only an upper limit for the lifetime of this 5^- state of < 2.91 ps which is in disagreement with the previous value by three orders of magnitude. We have no explanation for this disagreement except to say that the former measurement was the result of a β-decay study and the more current study exploits high precision methods for measuring the gamma-ray transition energy. It is possible that the former study was not able to resolve two gamma-rays that are nearly identical in energy. This state shows depopulating transitions to the $4^+, 5^+$ states of the ground state band and the $4^+, 5^+, 6^+$ states of the $K^\pi = 2^+_\gamma$ band. The origin of this state is likely of two quasiparticle origin and a precise lifetime instead of an upper limit would give us a benchmark for non-collective B($E1$)s.

B($E1$) values on the order of 4×10^{-6} W.u. are at the lower end of a non-collective B($E1$) value. The older measurement would lead to B($E1$) values in the 10^{-8} W.u. Still, the limit on the lifetime of this state yields B($E1$) values that are one to two orders of magnitude weaker than other B($E1$) values. Clearly further investigation is needed.

4. $K^\pi = 4^-$ *band or state at 1862.67 keV*

No other levels are known in this band. We were able to measure the lifetime of the 4^- state at 1862.67 to be in the range of 1.58 – 2.86 ps. This lifetime yields highly collective depopulating $E2$ transitions of approximately 5.3-13 W.u. from this band to the K$^\pi$ = 2^- band at 1148.23 keV, 6 – 11 W.u. to the K$^\pi$ = 5^- band (state) at 1485.67 keV, and $E1$ transitions of 0.6 – 3.2 mW.u. to the $4^+, 5^+$ states of the K$^\pi$ = 4^+ band at 1535.66 keV.

5. $K^\pi = 3^-$ *state at 1910.42 keV*

This state may be built on a K$^\pi$ = 2^- band at 1862.67 keV. We extract a lifetime for this state of 0.25 – 0.30 ps. This state depopulates to the 3^- state of the K$^\pi$ = 0^- band with a B($E2$) of 3.6 – 4.4 W.u. and to the 2^+, 3^+ ,4^+ states of the K$^\pi$ = 2^+ γ band with B($E1$) transitions of 0.3 to 0.6 mW.u.

IV. DISCUSSION

We have measured the level lifetimes of 12 states in ^{162}Dy using the (n, γ) reaction and the GRID technique to extract lifetimes. The limitations or largest uncertainties in this technique

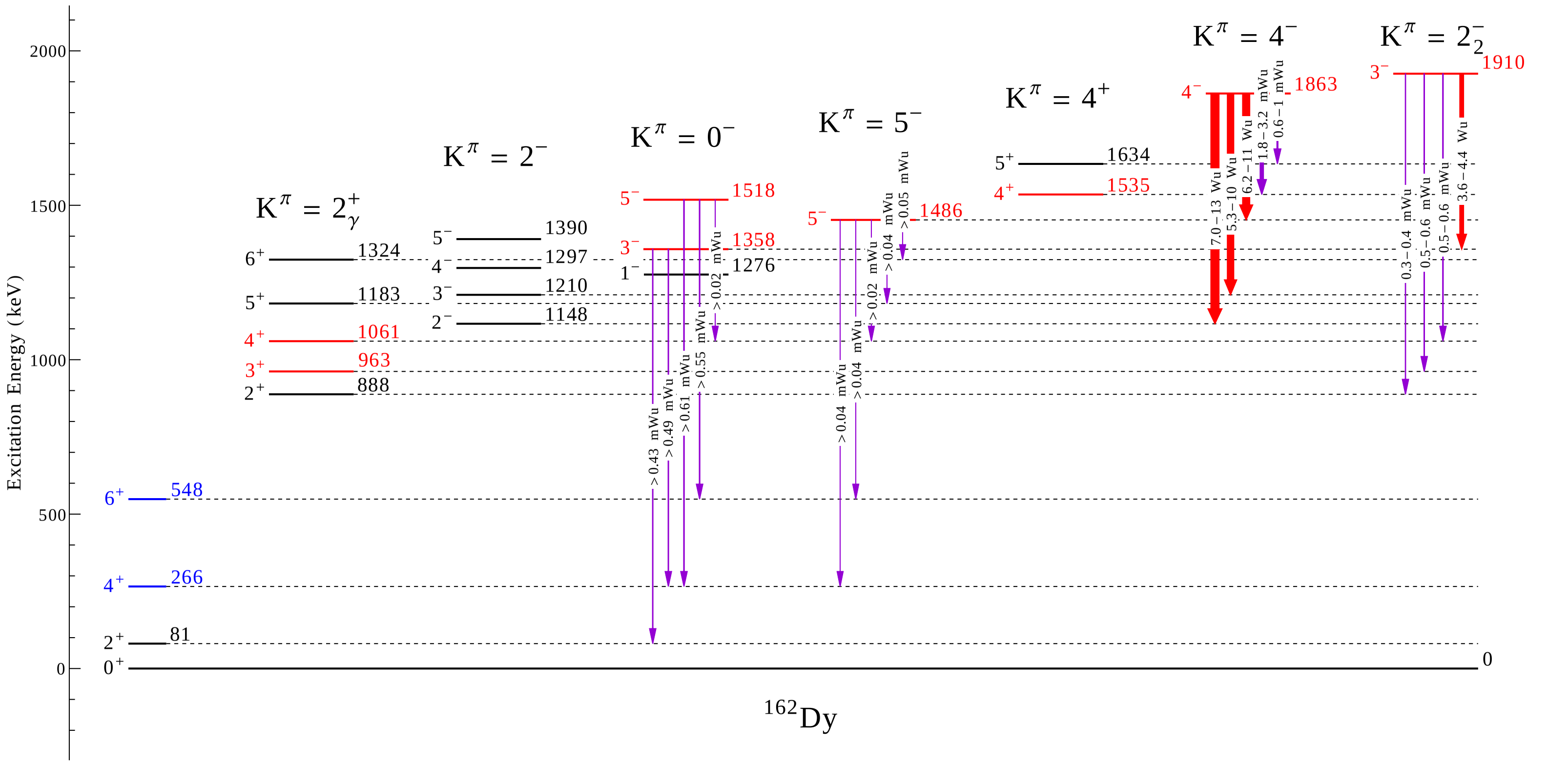

FIG. 4: Partial decay scheme for the negative parity K^π levels in ^{162}Dy.

of extracting level lifetimes lies in the unknown or missing feeding of a given level. Hence, we report ranges of lifetimes having simulated the missing feeding under extreme conditions to yield very conservative lifetime limits. Three of the level lifetimes that were measured here were previously measured by Coulomb Excitation. We fully agree with the lifetime of the 2^+ band head at 888.16 keV. We have measured an upper limit for the lifetime of the $1^-_{K^\pi=0^-}$ that is consistent with previous measurements while the lifetime of < 2.91 ps for the 1485.67 keV level is in complete disagreement with the former measurement of 2770 ± 160 ps. In GRID, we extract ranges of lifetimes due to the uncertainties associated with the missing feeding of a given level, hence, the ranges of B($E1$) and B($E2$) transitions. Table I shows the measured lifetimes for thirteen states, twelve of which have been measured with GRID. Table II shows the level energies, depopulating transitions, and the B($E2$) or B($E1$) values along with the relative intensities. Figures 3 and 4 summarize the positive and the negative parity bands and their preferred decay modes. The $K^\pi = 2^+$ band at 888.16 keV is clearly a γ vibration built on the deformed ground state of ^{162}Dy as evidenced by the collectivity of the transitions that depopulate the various members of this band to the ground state band. These B($E2$) values are typical for the rare-earth region of nuclei as demonstrated in Figure 1. The first excited $K^\pi = 0^+$ band with depopulating transitions prefer decay to the $K^\pi = 2^+_\gamma$ band in relative B($E2$) values based on transition intensities alone was often pointed out as a possible $\gamma\gamma$ vibrational phonon. In this work, we were able to measure the lifetime of the 4^+ member of this band and extracted ranges of B($E2$) values do not strongly exclude or include such an assignment. The transitions depopulating this state to the various members of $K^\pi = 2^+_\gamma$ band at the extremes show several W.u. of collectivity but at the lower end, we cannot distinguish between the B($E2$) ranges of the transitions that depopulate this state to the ground state and the γ band. On the other hand, the lifetime of the 1535.66 keV 4^+ state establishes clearly the preference of decay to the $K^\pi = 2^+_\gamma$ band indicating that is clearly an excitation built on the $K^\pi = 2^+$ "γ" band and most likely the two phonon $\gamma\gamma$ $K^\pi = 4^+$ excitation. There is also a second excited $K^\pi = 0^+$ band at 1666.27 keV with a related 2^+ state at 1728.31 keV that shows a preference of decay to the 2^+ state at 888.16 keV. Perhaps yet another vibrational excitation built on the $K^\pi = 2^+$ band? We would be tempted to call this $K^\pi = 0^+$ band at 1662.27 keV, a double phonon of the $\beta\gamma$ type but this is problematic in that a strong β- vibrational band is not yet observed in ^{162}Dy. The 4^+ state of the first excited $K^\pi = 0^+$ band at 1400.258 keV seems to be strongly connected to the 888.158 keV $K^\pi = 2^+$ γ-band. Fig. 3 summarizes the findings with respect to the positive parity bands.

For the negative parity states, we expect the octupole vibrational states to be fragmented in a deformed nucleus to $K^\pi = 0^-$, 1^-, 2^-, and 3^- bands. There were already several negative parity bands known in ^{162}Dy. Figure 4 summarizes the results shown in Tables I and II for the negative parity levels. The origin of the 5^- state at 1485.67 keV is likely of two quasiparticle origin and a precise lifetime instead of an upper limit would give us a clear benchmark for a non-collective B($E1$) value. We can however still benefit from the extracted limit of the level lifetime in this case. The transitions depopulating this state show B($E1$) values on the order of 10^{-5} W.u. This is typical of $E1$ transitions in the deformed rare earth region [54] but more enhanced B($E1$)s have been shown to indicate octupole vibrational excitations[55]. The work reported by Ref.[55] presented a computational approach to calculating the lowest axially symmetric octupole excitations in even-even nuclei. The $K^\pi = 0^-$ band and the depopulating B($E1$)s for ^{162}Dy are calculated in the 10^{-3} W.u range. To that end, the B($E1$) values from the $K^\pi = 0^-$ band indicate that this band is most likely the symmetric split of a possible octupole vibrational excitation built on the ground state band. The members of the $K^\pi = 0^-$ band show far more enhanced B($E1$) transitions connecting to the ground state band in comparison to the $K^\pi = 2^-$ band which had been identified as an octupole band in earlier work. The $K^\pi = 4^-$ band shows enhanced B($E2$) transitions connecting it to the $K^\pi = 2^-$ band and enhanced B($E1$) values connecting it to the $K^\pi = 4^+$ $\gamma\gamma$ band. The latter is likely due to the $\Delta K = 0$ preference while the B($E2$)s are robust and several W.u. in strength. We also report the lifetimes of the the 4^- state at 1862.67 keV and the 3^- state of the second excited $K^\pi = 2^-$ band starting at 1862.67 keV. The complete spectroscopic study of ^{162}Dy [42] closed with the request to procure lifetime measurements for the levels of this nucleus. In this work, we have attempted to deliver with lifetime measurements of 12 levels where 9 of the level lifetimes are measured for the first time. We have clear answers on the nature of single γ and double $\gamma\gamma$ vibrational excitations, an intriguing potential observation of a $\beta\gamma$ double vibrational excitation along with the caveat of an unobserved single β vibration as well as the fragmented octupole oscillations. Enhanced B(E1) values are correlated with octupole oscillations of a deformed nucleus and we see many enhanced B(E1) values. In addition, we see a clear single particle B(E1) benchmark but unanswered questions remain.

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TABLE II: Transition probabilities calculated from the known lifetimes in ^{162}Dy. The gamma ray intensities, conversion coefficients, assigned multi polarities are from Ref. [42]. In some cases, where no multipolarity assignments were made in Ref. [42] but multi polarities are deduced given the placements of the transitions, the multipolarity is reported in parenthesis in the table and the transition probabilities calculated in accordance. B($E1$) transition probabilities are reported in units of mW.u. (where $1mW.u. = 0.1916\ e^2b$). B($E2$) transition probabilities are reported in W.u. (where $1W.u. = 5.2461\text{x}10^{-7}e^2b^2$). The † indicates level lifetimes that were measured prior to this work. In one case, the previous measurement of the 1485.666 keV level lifetime (2780(190)ps)[53] is not in agreement with this work.

E_{lev} (keV)	E_γ (keV)	K_i^π,J_i^π	K_f^π,J_f^π	τ (ps)	πl	I_γ	B($E2$) (W.u.)	B($E1$) (mW.u.)	B($M1$) (μ_N^2)	Alaga
888.158	888.157	2^+,2^+_γ	0^+,0^+_{gs}	2.83 (11)[†]	E2	174.8(39)	4.71 (23)			1.00
	807.501		0^+,2^+_{gs}		96.7% E2	190.8(48)	8.00 (39)			1.43
	622.494		0^+,4^+_{gs}		E2	3.7(1)	0.59 (3)			0.08
962.936	882.276	2^+,3^+_γ	2^+,0^+_{gs}	0.36-4.09	99.3% E2	303.4(115)	5.9-66			1.00
	697.277		4^+,0^+_{gs}		94.8% E2	59.9(24)	3.6-40			0.40
1060.986	980.335	2^+,4^+_γ	2^+,0^+_{gs}	0.708-3.17	93% E2	67.9(25)	1.8-8.2			1.00
	795.327		4^+,0^+_{gs}		90% E2	115.0(54)	8.6-38			2.92
	512.464		6^+,0^+_{gs}		96.9% E2	1.82(7)	1.3-5.8			0.26
	172.835		2^+,2^+_γ		E2	0.82(3)	116-518			1.00
	98.054		2^+,3^+_γ		M1	0.09(1)			0.005-0.023	2.22
1148.226	260.067	2^-,2^-_1	2^+,2^+_γ	300 (60)[[†]	E1	129(2)		0.052 (5)		—

E_{lev} (keV)	E_γ (keV)	K_i^π,J_i^π	K_f^π,J_f^π	τ_{GRID} (ps)	πl	I_γ	B(E2) (W.u.)	B(E1) (mW.u.)	B(M1) (μ_N^2)	Alaga
	185.292		2^+,3_γ^+		E1	26.7(11)		0.029 (1)		—
1275.767	1275.81	0^-,1^-	0^+,0_{gs}^+	0.029 (5)	E1	30.3(8)		2.31 (41)		0.50
	1195.092		0^+,2_{gs}^+		E1	41.3(32)		3.83 (73)		1.00
1357.923	1277.271	0^-,3^-	0^+,2_{gs}^+	<0.214	E1	64.3(12)		>0.43		0.75
	1092.256		0^+,4_{gs}^+		E1	46.6(30)		>0.49		1.00
1485.666	1219.978	5^-,5^-	0^+,$4_{g.s.}^+$	<2.91	$E1$	26.6(8)		>0.04		—
	937.144		0^+,$6_{g.s.}^+$		$E1$	12(8)		>0.04		—
	424.676		2^+,4_γ^+		$(E1)$	0.48(3)		>0.02		—
	302.909		2^+,5_γ^+		$E1$	0.38(1)		>0.04		—
	275.582		2^-,3^-		$E2$	0.81(4)	>62			—
	188.663		2^-,4^-		$M1 + 44(13)\%E2$	0.25(2)	>47		>0.004	—
	161.209		2^+,6_γ^+		$(E1)$	0.0784(2)		>0.05		—
	95.158		2^-,5^-		$(E2\ (M1))$	0.45(2)	>7500		>0.14	—
1518.420	1252.744	0^-,5^-	0^+,4_{gs}^+	<0.193	E1	26(2)		>0.61		1.00
	969.908		0^+,6_{gs}^+		E1	10.9(4)		>0.55		1.20
	457.485		2^+,4_γ^+		E1	0.04(1)		>0.02		—
	160.489		0^-,3^-		E2	0.16(1)	>3265			—

E_{lev} (keV)	E_γ (keV)	K_i^π,J_i^π	K_f^π,J_f^π	τ_{GRID} (ps)	πl	I_γ	B(E2) (W.u.)	B(E1) (mW.u.)	B(M1) (μ_N^2)	Alaga
1535.660	987.150	4^+,4^+	6^+,0^+_{gs}	0.15-5.2	E2 (M1)	0.5(2)	0.02-0.71			—
	647.502		2^+,2^+_γ		94.4% E2	50.1(8)	16-551			1.00
	572.724		2^+,3^+_γ		89% E2	21.8(9)	12-418			0.56
	474.676		2^+,4^+_γ		27% M1	4.5(3)	5.2-180			0.20
	352.897		2^+,5^+_γ		62% E2	0.45(8)	2.0-66			0.04
	238.673		2^-,4^-		E1	0.06(1)		0.01-0.12		—
1574.288	1308.627	0^+_2,4^+	4^+,0^+_{gs}	1.08-3.1	E2 (M1)	24(2)	1.0-3.0			1.00
	1025.753		6^+,0^+_{gs}		60% E2	5.0(2)	0.4-1.3			1.75
	686.146		2^+,2^+_γ		E2	0.29(8)	0.3-0.9			1.0
	611.228		2^+,3^+_γ		E2 (M1)	0.12(2)	0.2-0.7			14
	513.314		2^+,4^+_γ		E2	0.51(3)	2.4-6.8			44
	391.541		2^+,5^+_γ		E2 (M1)	0.22(2)	4.0-11			44
	364.212		2^-,3^-		E1	0.116(7)		0.01-0.02		—
	277.285		2^-,4^-		E1	0.047(7)		0.01-0.02		—
	216.365		0^-,3^-		E1	0.060(7)		0.02-0.06		—
	120.819		0^+_2,2^+		E2	0.05(1)	320-920			—
1728.312	1647.617	0^+_3,2^+	0^+,2^+_{gs}	0.25-1.0	M1 (E2)[58]	12.7(11)	0.9-3.6		0.005 - 0.02	—
	1462.690		0^+,4^+_{gs}		E2	4.1(7)	0.52 - 2.09			—
	840.204		2^+,2^+_γ		E2 (M1)	0.5(2)	1.02 - 4.08			—
	452.535		0^-,1^-		E1	0.41(7)		0.08 - 0.32		1.00

E_{lev} (keV)	E_γ (keV)	K_i^π,J_i^π	K_f^π,J_f^π	τ_{GRID} (ps)	πl	I_γ	B(E2) (W.u.)	B(E1) (mW.u.)	B(M1) (μ_N^2)	Alaga
	370.389		0^-,3^-		E1	0.45(2)		0.16 - 0.64		0.25
	154.026		0_2^+,4^+		E2	0.073(9)	718.55- 2874			—
1862.672	714.444	4_1^-,4^-	2_2^-,2^-	1.58-2.86	88% E2	6.9(5)	6.99-12.65			1.00
	652.581		2_2^-,3^-		E2	2.92(9)	5.29-9.57			0.56
	377.015		5_1^-,5^-		E2 (M1)	0.22(1)	6.19-11.20		0.002-0.003	—
	327.012		4^+,4^+		E1	13.9(2)		1.80 -3.25		1.00
	228.263		4^+,5^+		E1	1.45(3)		0.55-1.00		0.25
1910.422	1022.278	2_2^-,3^-	2^+,2_γ^+	0.253-0.305	E1	8.3(5)		0.34-0.41		0.56
	947.484		2^+,3_γ^+		E1	8.9(3)		0.46-0.56		0.78
	849.435		2^+,4_γ^+		E1	7.1(2)		0.51-0.62		1.00
	552.486		0^-,3^-		E2 (M1)	0.89(13)	3.62-4.36		0.002-0.003	—

E_{lev} (keV)	E_γ (keV)	K_i^π,J_i^π	K_f^π,J_f^π	τ_{GRID} (ps)	πl	I_γ	B(E2) (W.u.)	B(E1) (mW.u.

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